International Journal of Academic Engineering Research (IJAER)
ISSN: 2643-9085
Vol. 9 Issue 11 November - 2025, Pages: 11-27

Blockchain-Enabled Traceability in Smart Manufacturing: Enhancing Data Integrity and Supply Chain Transparency

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Abstract: *The industry 4.0 era presents unprecedented opportunities for transforming manufacturing through digitalization. However, ensuring robust traceability and data integrity across complex global supply chains (SCs) remains a significant challenge, leading to issues like counterfeiting, quality control lapses, and inefficiencies. This research explores the synergistic potential of blockchain technology, integrated with the Internet of Things (IoT) Artificial Intelligence (AI), to establish highly secure, transparent, and immutable traceability systems within smart manufacturing (SM) environments. We delve into the fundamental concepts of these core technologies and propose comprehensive system architecture. The research critically examines diverse use cases across key sectors: automotive, pharmaceuticals, and electronics—highlighting tangible benefits such as enhanced product authentication, optimized recall management, and improved regulatory compliance. Concurrently, it addresses the multifaceted challenges, including scalability, interoperability, and cost. Ethical and regulatory considerations, specifically relating to data privacy and governance, are discussed in depth. Finally, the research outlines promising future research directions, including advancements in cross-chain interoperability, AI-driven analytics on blockchain data, and the role of these technologies in fostering sustainable development goals. The aim is to provide a holistic understanding of how this technological convergence can pave the way for more resilient, efficient, and trustworthy manufacturing ecosystems globally.*

Keywords: Blockchain, Smart Manufacturing, Industry 4.0, Traceability, Supply Chain Transparency, Cybersecurity.

INTRODUCTION

Industry 4.0, or the Fourth Industrial Revolution, is revolutionizing how we create products and services. This research explores how blockchain technology, combined with AI and IoT, can revolutionize traceability in SM. We discuss the challenges of existing traceability systems and how blockchain can address these by the provision of a secure, transparent, and immutable ledger of transactions. The research examines various use cases, including SC management, quality control, and regulatory compliance, highlighting the benefits of blockchain in these areas. Furthermore, we delve into the ethical considerations and future research focus associated with implementing decentralized ledger technology in SM. Our goal is to provide a detailed overview of how these technologies can work together to discover more efficient, transparent, and trustworthy manufacturing processes.

The Dawn of Smart Manufacturing (Industry 4.0)

Smart manufacturing, a core component of Industry 4.0, refers to the application of information and communication technologies (ICT) to the entire manufacturing process [1], [2]. It covers an extensive range of technologies, including IoT, AI, cloud computing, big data analytics, robotics, and additive manufacturing [1]. SM aims to develop highly efficient, flexible, and resilient production systems that can adapt to changing market demands and customer needs. Key characteristics of SM include interconnectivity, data-driven decision-making, automation, flexibility, customization, and sustainability [3], [4], [5], [6]. The evolution from previous industrial revolutions to Industry 4.0 signifies a paradigm shift towards fully digitized and interconnected manufacturing ecosystems.

Figure 1: Industry 4.0 / Smart Manufacturing Concepts

The Imperative of Traceability and Data Integrity

The rising complexity of global SCs makes the traceability of products and components crucial for several reasons. Traceability provides visibility into the SC, enabling better planning and coordination among stakeholders. It is also essential for quality control, regulatory compliance, and combating counterfeiting [6], [7], [8]. The integrity of data is essential for effective traceability[6]. Traditionally, traceability systems typically rely on centralized databases, which are prone to single points of failure, data manipulation, and opacity [6]. Blockchain technology offers a decentralized and immutable ledger that can defeat these limitations, ensure data integrity, and enhance traceability [6], [8], [9], [10], [11], [12], [13], [14], [15].

Blockchain as a Transformative Solution: Why Now?

Blockchain technology, characterized by decentralization, immutability, and transparency, presents an effective solution to the challenges of traceability and data integrity in smart manufacturing [16]. It provides a shared, distributed ledger where all transactions and product movements can be recorded securely and transparently [6], [10], [14]. The synergy of blockchain with AI and IoT increases to its potential. AI can interpret the data collected by IoT sensors and recorded on the blockchain, offering valuable insights for process optimization decision-making [1], [6], [15], [17], [18], [19], [20]. The suitability of this solution is emphasized by the rising complexity of SCs globally, the growing demand for ethically sourced and sustainable products, and the need for greater resilience in the face of disruptions [7], [19].

Research Objectives and Structure

This research aims to provide an overview of how blockchain technology, integrated with AI and IoT, can enhance traceability in smart manufacturing. We will study the basic concepts of these technologies, discuss their potential benefits and challenges, and examine various use cases across different industries. We organized the research as follows: Section 2 explores background knowledge on blockchain technology, SM, and traceability. Section 3 demonstrates proposed system architecture for blockchain-enabled traceability (BET). Section 4 delves into specific use cases in the automotive, pharmaceutical, and electronics industries. Blockchain technology comes with numerous advantages and pitfalls, section 5 explores those benefits and challenges and what its integration entails. Section 6 explores ethical and regulatory considerations. Section 7, finally, highlights future research directions in this rapidly developing field.

BACKGROUND CONCEPTS

Blockchain Technology Fundamentals

Blockchain is a distributed ledger technology (DLT) that allows multiple parties to record transactions securely and transparently. The set of transactions are packaged into blocks that are cryptographically linked to make it difficult to alter or tamper with the transactions. the previous one [6], [14], [15], [19], [21], [22], [23], [24]. Key features of blockchain include:

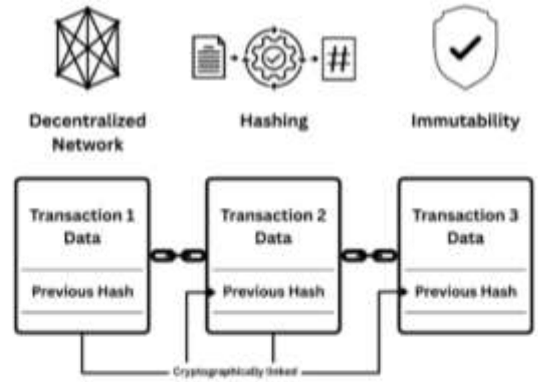

Figure 2: The concept of Blockchain

- **Decentralization:** Data in blockchain is stored across a network of computers, as opposed to central server making the system more resilient to failures and attacks [6], [21], [22].
- **Immutability:** Data in blockchain cannot be changed or deleted once recorded, ensuring the integrity and trustworthiness of the recorded data [21], [22].
- **Transparency:** While the identities of participants can be kept confidential, the transactions themselves are transparent and can be audited by authorized parties[21], [22], [25].
- **Security:** Cryptographic techniques are used to secure transactions and protect against unauthorized access [13], [20], [24].

Types of blockchains include Public (e.g., Bitcoin, Ethereum), Private (access restricted to specific organizations), and Consortium (controlled by a group of organizations) blockchains [6], [19], [21], [22], [26]. Smart contracts allow the parties to a transaction to verify and automatically enforce the terms of their agreement, eliminating the need for third parties and enabling rapid and secure outcomes [6], [21], [25].

Smart Manufacturing and Industry 4.0 Revisited

Smart manufacturing, which is a core component of Industry 4.0, refers to the use of information and communication technologies (ICT) throughout the entire manufacturing process [1], [2], [4], [27], [28]. It makes use of technologies like IoT, AI, big data analytics, cloud computing, robotics, and additive manufacturing [1], [3], [4], [27], [29]. The goal here is to create more efficient, resilient, and flexible production systems that can adapt to the dynamics of the market and customer needs. Key characteristics of SM include:

- **Interconnectivity:** People, machines, and systems, and are interconnected and communicate with each other in real-time [3], [4], [30].

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- **Data-driven Decisions:** Data collected from various sources is analyzed to gain insights and make informed decisions[3], [5], [8], [28].
- **Automation:** Repetitive and complex tasks are automated to improve efficiency and reduce errors [3], [4], [31].
- **Flexibility and Customization:** Production systems are easily reconfigured to produce a range of products in small batches, meeting the demand for mass customization [3], [32].

Table 1: Comparison of Blockchain Platforms for Manufacturing Traceability

Feature	Hyperledger Fabric [15], [21], [36], [37]	Ethereum [6], [10], [15], [19], [26], [36]	VeChain Thor [38], [39]	Considerations
Type	Permissioned	Permissionless/ Permissioned	Permissioned	Permissioned networks are preferred for enterprise use due privacy, and governance [21], [36], [37].
Consensus	Pluggable (e.g., Raft, PBFT)	Proof-of-Work (PoW) / Proof-of-Stake (PoS)	Proof-of-Authority (PoA)	Consensus mechanism impacts transaction speed, finality, energy consumption, and security. PoA/PBFT/Raft are often faster [23], [37], [40].
Smart Contracts	Chaincode (Go, Node.js, Java)	Solidity, Vyper	Solidity	Language flexibility and maturity of smart contract development tools are important. Gas fees can be a concern [10], [17], [19], [37].
Performance	High throughput, low latency	Lower throughput, variable latency	Moderate to High throughput	Scalability and transaction speed are critical for high-volume manufacturing data [6], [39], [40].
Governance	Defined by consortium	Off-chain governance, community-driven	VeChain Foundation	Clear governance models are essential for managing upgrades, disputes, and access control [14], [18], [37], [40], [41], [42].

- **Sustainability:** SM practices aim to enhance resource usage, cut waste, and reduce environmental damage [3], [32].

Cyber-Physical Systems (CPS) are foundational to smart factories, merging physical operations with digital connectivity for autonomous decision-making [28], [29], [33], [34]. However, implementing Industry 4.0 faces challenges such as infrastructure limitations and the digital skills gap [17], [30], [35].

Data Privacy	Channels, confidential data collections	Limited on public chain; private chains offer more	Controllable data access	Granular data privacy controls are crucial for protecting sensitive manufacturing and SC information [6], [17], [18], [31], [37].
Cost	Infrastructure & operational costs	Gas fees, infrastructure	Transaction fees (VTHO)	Costs include initial setup, ongoing operations, and transaction fees [6], [8], [11], [37], [43].
Ecosystem	Strong enterprise adoption, Linux Foundation support	Large developer community, extensive tooling	Strong focus on SC & IoT	Maturity, available tools, and community support can impact implementation and maintenance [23], [38], [41], [44].
Suitability for Traceability	High: Designed for enterprise, reliable performance	Moderate to High: Public transparency vs. private control	High: Specifically for SC	Hyperledger Fabric and VeChain Thor are often cited for SC. Ethereum offers flexible alternatives [37].

The Role of AI in Manufacturing Systems

AI and Machine Learning (ML) are increasingly applied in manufacturing for several reasons like predictive maintenance, process optimization, demand forecasting and quality control. AI can interpret the data generated by IoT sensors in a smart factory to recognize patterns, predict failures, and optimize processes [18], [19], [45]. The synergy between AI and blockchain is significant: AI analyze blockchain data for insights, while blockchain provides a secure and auditable trail for AI models and their training data [6], [17], [18]. Edge AI, where AI computation is performed locally on devices rather than in a centralized cloud, offers benefits in terms of speed and data privacy for manufacturing applications[46].

Supply Chain Traceability: Needs and Current Limitations

Traceability in SC is the ability to keep track of product or component from its origin (raw materials) throughout the stages of production, processing, and distribution to the end consumer [25], [37], [43]. Robust traceability is crucial for:

- **Quality Control and Assurance:** Identifying and isolating defective products or batches quickly [7], [8].
- **Regulatory Compliance:** Meeting industry-specific standards and legal requirements (e.g., food safety, pharmaceutical tracking) [8].
- **Combating Counterfeiting and Fraud:** Ensuring product authenticity and preventing illicit trade [37].
- **Supply Chain Optimization:** Identifying bottlenecks and inefficiencies [15].
- **Consumer Trust and Transparency:** Providing consumers with information about product origin, ingredients, and ethical sourcing [13].

Limitations of traditional traceability systems often include reliance on centralized databases vulnerable to single points of failure or manipulation, paper-based systems prone to errors and inefficiencies, and a lack of interoperability between different stakeholders' systems. This fragmentation hinders end-to-end visibility and trust [11], [13], [37].

Table 2: AI Techniques in Blockchain-Enhanced Smart Manufacturing Traceability

AI Technique	Description	Application in Traceability & SM	Potential Benefits

Machine Learning (ML)	Algorithms that allow systems to learn from data without being explicitly programmed [45].	Predictive maintenance of machinery [18], [47], quality control in production lines [18], demand forecasting, anomaly detection in SC data[18], optimizing logistics.	Increased efficiency, reduced downtime, improved product quality, cost savings, proactive risk management.
Natural Language Processing (NLP)	Enables computers to understand, interpret, and generate human language.	Analyzing customer feedback for product improvement, extracting insights from unstructured data in SC reports, voice-activated commands for machinery control, automated customer service chatbots [1], [31], [45].	Enhanced customer satisfaction, better understanding of market trends, improved operational efficiency through voice commands, streamlined communication.
Computer Vision	Enables computers to "see" and interpret visual information from images or videos [45].	Automated quality inspection of products, visual tracking of goods in warehouses and transit, facial recognition for secure access to facilities, robotic guidance in assembly lines [45].	Improved accuracy in quality control, enhanced security, optimized logistics and inventory management, reduced human error.
Expert Systems	AI systems that emulate the decision-making ability of a human expert in a specific domain [17].	Providing diagnostic support for equipment malfunctions, offering decision support for complex SC optimization problems, guiding regulatory compliance processes [17].	Consistent and high-quality decision-making, knowledge retention, reduced reliance on individual human experts.
Robotics and Automation	Use of robots and automated systems to perform tasks.	Automated material handling, assembly, packaging, and inspection in manufacturing; autonomous vehicles for logistics and delivery [2], [4].	Increased production speed, reduced labor costs, improved precision and consistency, enhanced worker safety.
Predictive Analytics	Uses historical data, statistical algorithms, and ML techniques to predict future outcomes [3].	Forecasting demand for products, predicting potential SC disruptions, identifying patterns that might indicate fraudulent activities, optimizing inventory levels [3], [18], [29].	Better resource allocation, proactive risk mitigation, improved SC resilience, enhanced fraud detection.
Anomaly Detection	Identifying rare items, events or observations which raise suspicions by differing notably from the norm [34].	Detecting unusual patterns in sensor data from machinery (predictive maintenance), identifying outliers in financial transactions related to the SC, flagging suspicious activities in logistics [18], [37].	Early detection of potential problems, prevention of costly failures or security breaches, improved operational integrity.
Reinforcement Learning (RL)	An area in ML that deals with how software agents should act in an environment to maximize their cumulative reward.	Optimizing complex scheduling and routing problems in logistics, training autonomous robots for dynamic manufacturing environments, adaptive control systems for energy efficiency [45].	Highly optimized and adaptive solutions for complex, dynamic problems, continuous improvement of processes.

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SYSTEM ARCHITECTURE: BLOCKCHAIN-ENABLED TRACEABILITY (BET)

Proposed Decentralized Architecture

The proposed system architecture for BET in SM integrates several key technologies to ensure secure, transparent, and efficient tracking of products and processes. This architecture is designed to be decentralized, leveraging the inherent strengths of blockchain technology. It comprises the following layers:

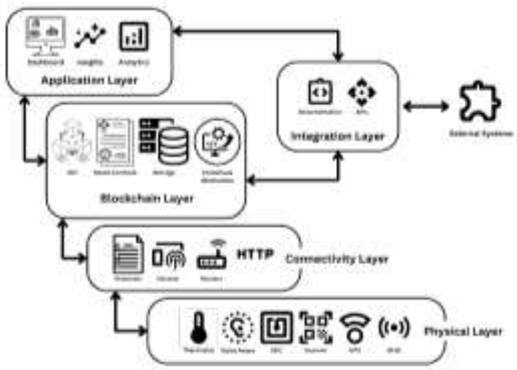

Figure 3: Proposed System Architecture

1. **Physical Layer/Data Acquisition Layer:** This is the foundational layer where data originates. It consists of IoT devices, sensors, barcode scanners, and other data capture mechanisms embedded within the manufacturing floor, warehouses, and logistics network. These devices collect real-time data related to raw materials, components, work-in-progress, finished goods, environmental conditions, and process parameters.
2. **Connectivity/Communication Layer:** This layer is to securely transmit the data acquired by the physical layer to the blockchain network. It utilizes various communication protocols like secure Hypertext Transfer Protocol (HTTPS), Constrained Application Protocol (CoAP), Message Queuing Telemetry Transport (MQTT), or Advanced Message Queuing Protocol (AMQP) connections. Ensuring reliable and secure data transmission is crucial to maintaining data integrity from the source.
3. **Blockchain Layer (Distributed Ledger Technology):** This is the core of the traceability system. It involves:

   - **Choice of Blockchain Platform:** Depending on the requirements, this could be public, private, or consortium. For enterprise-grade traceability, permissioned blockchains like Hyperledger Fabric are often preferred due to their control over participants, scalability, and privacy features [36], [37].

   - **Smart Contracts:** These are self-enforcing agreements coded into the blockchain [21] and automate activities such as verifying compliance, triggering actions based on predefined conditions (e.g., when temperature exceeds a threshold), and managing access rights to data [6], [14], [16], [17], [21], [25]. For instance, a smart contract can automatically log a quality check failure if sensor data indicates a deviation from standards.

   - **Data Storage:** While transactional data and critical metadata are stored on-chain for immutability and auditability, large datasets might be stored off-chain with their hashes or references stored on the blockchain to ensure integrity and reduce blockchain bloat [13].

   - **Consensus Mechanism:** The chosen mechanism ensures that participants agree on transactions are valid before adding them to the network.

4. **Application Layer:** This layer consists of the user interface and other tools for various stakeholders to interact with the traceability system. This includes:

   - **Dashboards and Visualization Tools:** For monitoring the SC, tracking products in real-time, and visualizing key performance indicators.

   - **Reporting and Analytics Tools:** Leveraging AI and ML algorithms to analyze the data stored on or linked from the blockchain. This provides insights into process efficiency, identify bottlenecks, predict potential quality issues, and support decision-making.

   - **APIs for Integration:** Allowing seamless integration with existing enterprise systems such as Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES), and Warehouse Management Systems (WMS).

5. **Integration Layer:** This layer ensures effective communication and exchange of data between the blockchain solution and other existing enterprise systems and external partner systems. This is essential for producing a comprehensive SC overview and facilitating end-to-end traceability.

The Role of IoT Sensors and Data Flow

IoT devices are the primary data sources in this BET system. They bridge the physical world with digital ledger.

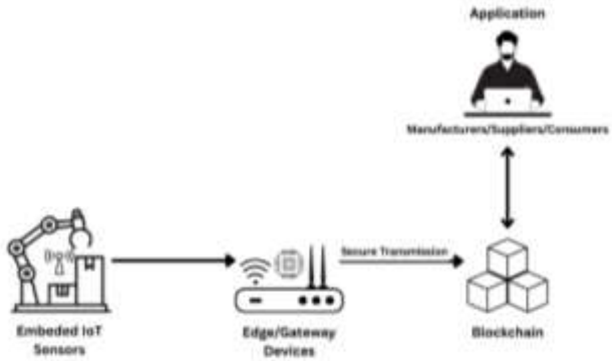

Figure 4: IoT-Blockchain Integrated System in Smart Manufacturing

- **Data Generation:** Sensors embedded in machinery, attached to components, or monitoring the environment continuously generate data. This includes unique identifiers (e.g., RFID tags), location data, environmental conditions (temperature, humidity), and operational parameters (machine status).
- **Data Transmission:** This raw data is transmitted securely, often via gateways, to the blockchain network or an intermediary processing layer.
- **Data Validation and Formatting:** Before being recorded on the blockchain, data might undergo initial validation and formatting to ensure consistency and relevance. Smart contracts can play a role here by enforcing specific data structures or rules.
- **Immutable Record Creation:** Once validated, critical data points are recorded as transactions on the blockchain, creating an immutable and auditable trail. For example, a sensor reading indicating a temperature deviation for a perishable good would be logged, along with a timestamp and device ID.

AI Integration for Real-Time Decision Making and Anomaly Detection

AI and ML algorithms can significantly enhance the value derived from the vast amounts of data collected and stored within the traceability system [6].

- **Predictive Analytics:** AI can analyze historical and real-time data from IoT sensors and blockchain records to predict potential issues [1], [18]. For instance, predictive maintenance algorithms can anticipate equipment failures, or AI can utilize known patterns to anticipate disruptions in the SC.
- **Anomaly Detection:** ML models can be trained to identify unusual patterns or deviations from normal operating parameters [18]. This could include detecting fraudulent transactions, identifying counterfeit products by flagging inconsistencies in their digital trail, or notifying quality control issues in real-time.
- **Process Optimization:** AI can analyze traceability data to identify inefficiencies in the manufacturing or logistics processes and suggest optimizations [18].
- **Enhanced Quality Control:** AI can analyze sensor data and images (e.g., from visual inspection systems) to automatically assess product quality against predefined standards [18], logging results on the blockchain.

Smart Contracts for Automation and Verification

Smart contracts are fundamental in automating processes and enforcing rules within the BET system [6], [10], [14], [21].

- **Automated Compliance Checks:** Smart contracts can automatically verify if products or processes meet predefined regulatory or quality standards [6]. For example, if a shipment of temperature-sensitive goods experiences a deviation, a smart contract could automatically flag it or even prevent its acceptance at the next stage.
- **Conditional Transactions:** Payments to suppliers can be automatically triggered by a smart contract once goods are verified as received and meeting quality specifications [6], [13], [39], as recorded on the blockchain.
- **Access Control Management:** Smart contracts can manage permissions [18], defining who can view or add data to specific parts of the blockchain, ensuring data privacy and security while maintaining transparency among authorized parties.
- **Dispute Resolution:** In case of discrepancies (e.g., quantity or quality disputes), the immutable record on the blockchain, governed by smart contracts, can provide a trusted basis for resolution [6], [25].
- **Tracking and Alerts:** Smart contracts can monitor specific events or conditions and automatically trigger alerts or notifications to relevant stakeholders [37]. For example, alerting a manager if a critical component is running low in inventory based on real-time consumption data logged on the blockchain.

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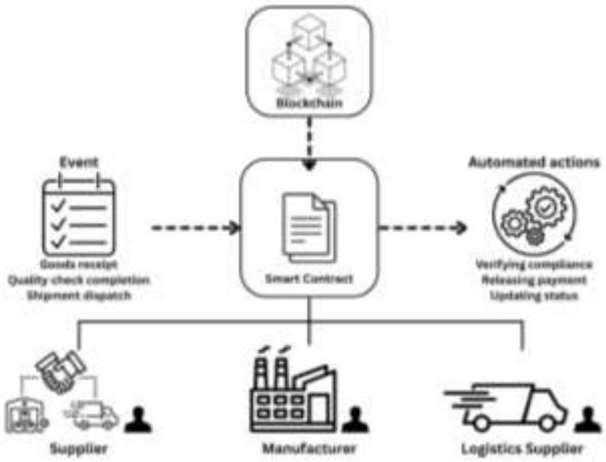

Figure 5: Smart Contract interaction

By combining these technological layers, a BET system can provide a robust, transparent, and intelligent solution for modern SM environments, addressing most challenges of the traditional systems.

USE CASE SCENARIOS IN KEY SECTORS

Blockchain technology, when integrated with SM principles, offers transformative solutions for traceability across various industrial sectors. The ability to create immutable, transparent, and auditable ledger of transactions and product movements addresses critical challenges of quality control, regulatory compliance, anti-counterfeiting, and SC optimization. This section explores specific use cases in key sectors, illustrating the practical applications and benefits of BET.

Automotive Supply Chain Traceability

The automotive industry is characterized by complex, multi-tiered SCs involving hundreds of suppliers for thousands of components that make up a single vehicle. Ensuring the authenticity, quality, and compliance of each part is paramount for safety, regulatory adherence, and brand reputation.

Figure 6: Blockchain-Enabled Automotive Supply Chain Traceability Use Case

Challenges:

- **Counterfeit Parts:** The influx of counterfeit automotive parts poses significant safety risks and economic losses [6], [11], [48].
- **Recall Management:** Inefficient recall processes can be costly and damage consumer trust. Identifying affected vehicles and specific faulty components can be a logistical nightmare [48], [49].
- **Compliance and Certification:** Meeting stringent safety and environmental regulations requires meticulous tracking and documentation of parts and processes [6], [20], [43].
- **Supply Chain Opacity:** Lack of transparency can lead to inefficiencies, delays, and difficulties in pinpointing issues [25], [50].

Blockchain Solution & Benefits:

- **Component Pedigree Tracking:** Each component can be assigned a unique digital identity at its point of origin. As the component moves through the SC, each transaction and quality check is recorded on an immutable distributed ledger [32]. This creates a verifiable digital passport for every part.
- **Enhanced Recall Management:** In the event of a defect, manufacturers can quickly and accurately trace the affected batch of components and the specific vehicles they were installed in, enabling targeted and efficient recalls [6], [8], [25], [43]. This minimizes costs and reputational damage.
- **Combating Counterfeits:** By providing a verifiable record of authenticity and provenance, blockchain makes it significantly harder for counterfeit parts to enter and circulate within the legitimate SC [6], [20], [25], [43]. Consumers and service centers can verify the genuineness of parts.
- **Improved Regulatory Compliance:** Blockchain provides a transparent and auditable trail for all components and processes, simplifying compliance with safety standards and environmental regulations [6], [25], [32], [51].
- **Increased Supply Chain Transparency & Efficiency:** All authorized participants in the automotive value chain can access relevant, real-time information, improving coordination, reducing information asymmetry, and streamlining logistics [6], [32], [46], [52].
- **Smart Contracts for Automation:** Smart contracts can automate activities like payments upon verified delivery and acceptance of components, or trigger alerts if a non-compliant part is detected [25], [46].

Pharmaceutical Product Authentication and Cold Chain Monitoring

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The pharmaceutical industry has challenges of counterfeit drugs, drug diversion, and preserving the value of temperature-sensitive medicines throughout the SC .

Figure 7: Blockchain-enabled pharmaceutical product authentication and cold chain monitoring use case.

Challenges:

- **Counterfeit Drugs:** Fake or substandard medicines pose severe health risks to patients and cause significant economic losses and reputational damage to legitimate manufacturers [13], [26], [37], [53].
- **Drug Diversion:** Theft or illicit redirection of drugs from the legitimate SC [37], [54].
- **Cold Chain Integrity:** Many vaccines and biologic drugs require strict temperature control during storage and transportation. Breaks in the cold chain can render these products ineffective or even harmful [37], [55].
- **Regulatory Compliance:** Stringent regulations like the Drug SC Security Act (DSCSA) in the U.S. mandate traceability and verification of pharmaceutical products [13], [55].

Blockchain Solution & Benefits:

- **Track-and-Trace Systems:** Blockchain can establish an immutable and auditable trail for pharmaceutical products from the point of manufacture, through distribution channels, to the pharmacy or healthcare provider, and to the patient [6], [54]. Each transaction is recorded on the blockchain, often linked via serialized product codes (e.g., 2D barcodes).
- **Enhanced Product Authentication:** Patients and healthcare providers can confirm the genuineness of a drug by scanning its code and checking its provenance on the blockchain, drastically reducing the danger of counterfeit drugs entering the system [13], [26], [37].
- **Real-time Cold Chain Monitoring:** Integrating IoT sensors (temperature, humidity) with the blockchain allows for continuous monitoring of environmental conditions during the storage and transport of temperature-sensitive drugs [37]. Any deviation from prescribed conditions can be recorded as an immutable event on the blockchain, triggering alerts and enabling verification of product integrity before administration [6], [37].
- **Improved Regulatory Compliance:** Blockchain-based systems can help pharmaceutical companies meet complex track-and-trace regulations by providing a secure, transparent, and easily auditable history of a drug's journey throughout the SC [26], [55].
- **Efficient Recall Management:** In the event of a product recall, blockchain enables rapid identification and location of affected batches, minimizing patient risk and logistical costs [8], [53].
- **Prevention of Diversion and Theft:** The enhanced visibility and traceability provided by blockchain can help deter and detect drug diversion and theft [37].

Electronics Component Lifecycle Tracking and Anti-Counterfeiting

The electronics industry, with its globalized and often complex SCs, faces challenges related to counterfeit components, ensuring ethical sourcing, and managing electronic waste (e-waste).

Challenges:

- **Counterfeit Electronic Components:** Fake or substandard components (e.g., microchips, capacitors) can lead to product failures, safety hazards, and significant financial losses. These are often difficult to detect [20], [56].
- **Ethical Sourcing and Conflict Minerals:** Ensuring that raw materials used in electronic components (e.g., tin, tantalum, tungsten, gold) are not sourced from conflict zones or involve unethical labor practices [57], [58].
- **E-waste Management and Circular Economy:** Tracking components at their end-of-life is crucial for responsible recycling, recovery of valuable materials, and reducing environmental impact [59].
- **Supply Chain Complexity and Opacity:** Diverse global suppliers and intricate manufacturing processes can make it difficult to maintain visibility and control [11], [13], [37].

Blockchain Solution & Benefits:

- **Component Provenance and Authenticity:** Assigning unique digital identities to electronic components and recording their journey from raw material extraction, through manufacturing stages, to assembly and distribution on a blockchain can create an irrefutable record of origin and authenticity [8], [25], [36], [56]. This helps combat counterfeit components by making it easy to verify genuine parts.

- **Ethical Sourcing Verification:** Blockchain can provide a transparent and auditable trail for raw materials, helping companies demonstrate compliance with regulations like the Dodd-Frank Act [60] and meet consumer demands for ethically sourced products. Each transaction in the mineral SC can be recorded, from mine to manufacturer [6], [25].

- **Enhanced E-waste Management and Circularity:** By tracking electronic components throughout their lifecycle, blockchain can facilitate more efficient and responsible e-waste recycling [20], [41]. Information about the materials contained in a component, its age, and its previous uses can be securely stored and accessed, aiding in the recovery and recycling of valuable resources and encouraging a circular economy.

- **Improved Supply Chain Transparency and Security:** A shared, immutable ledger can increase trust and transparency among all stakeholders in the electronics SC, from raw material suppliers to manufacturers, distributors, and recyclers [15], [36], [42], [57]. This can also aid in identifying and mitigating risks like component shortages or disruptions.

- **Smart Contracts for Compliance:** Smart contracts can automate checks for compliance with environmental regulations or ethical sourcing standards at various points in the SC [6], [9], [11], [37].

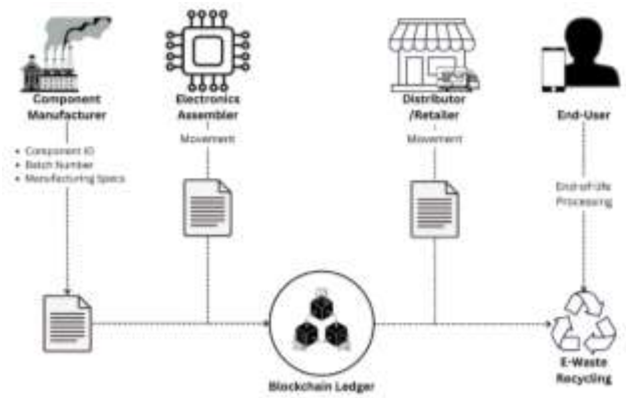

Figure 8: Blockchain for electronics component lifecycle tracking

BENEFITS AND CHALLENGES

Integrating blockchain technology into SM traceability systems offers a plethora of advantages that can significantly enhance operational efficiency, security, and stakeholder trust. However, its widespread adoption is not without challenges and limitations that need careful consideration and mitigation.

Key Advantages of Blockchain-Enabled Traceability

- **Enhanced Security and Data Integrity:** Blockchain provides a shared, distributed ledger for all transactions and product movements to be recorded chronologically and cannot be altered once validated [6], [9], [22], [25]. Through cryptographic hashing, digital signatures, and decentralized consensus mechanisms, it secures data against unauthorized access and tampering [8], [23]. This ensures integrity and reduces fraudulent activities.

- **Increased Transparency:** The technology creates an unprecedented level of transparency for all authorized participants in the SC, from raw material suppliers to end consumers [6], [11], [15], [18]. This shared, auditable record fosters trust among SC partners.

- **Improved Efficiency and Automation:** Smart contracts can automate various SC processes. This includes automated quality checks, compliance verification [6], conditional payments upon successful delivery or quality confirmation [37], and streamlined recall management[6]. Automation reduces manual effort, minimizes delays, and lowers operational costs [6], [25], [47].

- **Greater Accountability and Auditability:** Every transaction on the blockchain is timestamped and linked to a specific participant (or their digital identity) [11], [17]. This creates a clear and verifiable audit trail, which makes it easier to track responsibility, identify the source of defects or issues, and ensure compliance with industry regulations and standards [18], [21], [42].

- **Reduced Fraud and Counterfeiting:** The inherent transparency and immutability of blockchain make it significantly more difficult to introduce counterfeit products into the SC or manipulate traceability data [9], [13], [25], [26], [37]. By allocating unique digital identities to products and tracking their movement on the blockchain, manufacturers can provide verifiable proof of authenticity, thereby protecting their brand reputation and consumer safety [15], [43].

- **Enhanced Compliance and Auditability:** Blockchain offers a robust mechanism to demonstrate compliance for industries with strict regulatory constraints, like pharmaceuticals and food safety [8], [18], [25], [36], [37]. Verifiable and auditable records of product handling, quality control, and adherence to standards can simplify compliance reporting and inspections [8], [32].

- **Increased Trust among Supply Chain Partners:** Blockchain promotes greater collaboration and trust among partners by centralizing the source of truth that is accessible to all permissioned stakeholders [7], [9], [11], [25], [39], [42]. This shared visibility can lead to better coordination, reduced disputes, and more resilient SC ecosystems.

Technical and Operational Challenges

- **Scalability:** Public blockchain networks, and even some permissioned ones, can face limitations of throughput (transactions per second) and data storage capacity [19], [20], [22], [39]. High-volume manufacturing environments generate vast amounts of data, ensuring that the blockchain can manage this load without compromising performance or incurring excessive latency is a critical challenge [25].

- **Energy Consumption:** Some consensus mechanisms, notably PoW used by Bitcoin, are highly energy-intensive [18], [24], [40]. While enterprise blockchains often use consensus algorithms that use less energy (e.g., Raft), energy consumption remains a consideration, especially for sustainability-focused initiatives [37], [40].

- **Latency:** Transaction confirmation times on some blockchain networks can be a bottleneck for real-time traceability applications in fast-paced manufacturing environments [15], [19], [37].

- **Interoperability:** Ensuring smooth and secure interoperability between new blockchain platforms and existing legacy IT systems, as well as between different blockchain networks used by various SC partners, can be technically complicated and demanding [6], [19], [25], [37], [40].

- **Data Standardization:** The lack of universally accepted industry standards for data representation, communication protocols, and smart contract design can create integration challenges and hamper smooth exchange of data among different systems and platforms. [6], [25], [40]

- **Cost of Implementation:** Implementing and maintaining a blockchain solution can involve significant upfront investment in infrastructure, software development, integration, and specialized expertise. Operational costs, including potential transaction fees and system maintenance [6], also need to be considered.

- **Complexity:** Designing, developing, deploying, and managing blockchain applications requires specialized knowledge in areas like cryptography, distributed systems, and smart contract programming, which may not be readily available [6].

- **The "Garbage In, Garbage Out" Problem:** Blockchain ensures the immutability of data once it is on the chain, but it cannot guarantee the accuracy or authenticity of the data at the point of entry. If incorrect or fraudulent data is fed into the blockchain, the system will faithfully record and perpetuate this erroneous information [37]. Robust data validation mechanisms and secure oracles are crucial [37].

ETHICAL AND REGULATORY CONSIDERATIONS

The widespread adoption of blockchain, AI, and IoT in SM traceability systems, despite having significant benefits, introduces a complex array of ethical and regulatory considerations that must be proactively addressed to ensure responsible innovation and societal acceptance [17], [18], [31], [37].

Data Ownership, Privacy, and Confidentiality

- **Data Ownership:** In a multi-stakeholder SC, determining who owns the enormous amount of data from IoT devices and recorded on the blockchain can be challenging. Clear agreements and governance models are needed to define data ownership rights and responsibilities for data generated by sensors, manufacturing processes, and logistics. [6], [31]

- **Data Privacy:** While blockchain can enhance transparency, it also raises privacy concerns, especially if personally identifiable information (PII) or commercially sensitive data is recorded [6], [14], [31], [41]. Compliance with data privacy regulations like the GDPR in Europe is paramount [6], [22], [23], [31]. Techniques such as zero-knowledge proofs, private channels, data anonymization, and pseudonymization must be employed to protect sensitive information while still allowing for verification and traceability [6], [9], [19], [22], [36], [39]. The choice between public, private, and consortium blockchains also significantly impacts privacy levels.

- **Data Security:** Although blockchain itself is cryptographically secure, vulnerabilities can exist at the endpoints (IoT devices, user interfaces), in smart contract code, or in off-chain data storage [18], [37]. Robust cybersecurity measures, regular audits of smart contracts, secure key management practices, and end-to-end encryption are crucial to prevent data breaches and unauthorized access [18], [37].

Compliance with Industrial Standards and Regulations

- **Evolving Regulatory Landscape:** The legal and regulatory framework for blockchain and AI is still developing in many jurisdictions. Companies implementing these technologies must stay abreast of evolving laws related to data governance, digital signatures, smart contract enforceability, and liability in automated systems [18], [25].

- **Lack of Standardization:** The absence of universally accepted standards for blockchain interoperability, data formats, and communication protocols can hinder widespread adoption and create integration challenges. Industry collaborations and government initiatives are needed to foster standardization for blockchain-based traceability systems. [6], [11], [18], [31]

- **Cross-Border Data Flows:** Global SCs involve data moving across multiple jurisdictions, each with its own set of regulations [32]. Managing compliance with these diverse and sometimes conflicting legal requirements for data transfer and storage is a significant challenge [6], [21].

Governance of Blockchain Systems

Effective governance models are crucial for managing permissioned blockchain networks involving multiple stakeholders. These models need to define rules for participation, data access, dispute resolution, system upgrades, and changes to smart contracts [6], [25]. Establishing fair and transparent governance mechanisms that balance the interests of all participants is key to the long-term success and sustainability of blockchain-based traceability systems.

Social and Economic Implications

- **Impact on Employment and Skills Gap:** Automation driven by AI and robotics in SM can lead to job displacement for workers performing routine tasks [1], [6], [30]. Simultaneously, there is a growing demand for new skills in data science, blockchain development, and AI ethics [1], [2], [6], [30]. Addressing this requires investment in reskilling and upskilling programs, as well as educational reforms to prepare the workforce for the future of manufacturing [6].
- **Ensuring Equitable Access:** The implementation of advanced technologies like blockchain and AI can be costly [6], potentially widening the digital divide between large corporations and Small and Medium-sized Enterprises (SMEs) [6], [37]. Efforts should be made for these technologies to be more accessible and affordable, ensuring that the benefits of SM are shared equitably[42] .
- **Potential for Empowering Small Producers:** Conversely, well-designed blockchain systems can empower small producers by providing them with direct access to markets, fair pricing mechanisms, and verifiable proof of their product quality and ethical practices. [6], [20]
- **Accountability and Liability:** In complex, automated systems where decisions are made by AI or executed by smart contracts, determining accountability in case of errors, failures, or harm can be difficult. Clear legal frameworks are needed to assign responsibility when autonomous systems cause unintended consequences [13].

Addressing these ethical and regulatory considerations requires a multi-faceted approach involving technological solutions, robust governance frameworks, industry collaboration, and proactive engagement with policymakers and civil society. A commitment to responsible innovation will be vital for harnessing the full potential of these transformative technologies for the benefit of all stakeholders.

FUTURE RESEARCH DIRECTIONS

The integration of blockchain, AI, and IoT for traceability in SM is a rapidly evolving field, and while significant progress has been made [8], [11], [18], [19], [25], [42], [43], [54], several promising avenues for future research remain [6], [25], [26]. A focus on these areas will be critical for unlocking the full potential of these technologies and overcoming existing limitations.

Enhanced Interoperability and Standardization

- **Cross-Chain Interoperability:** Currently, many blockchain platforms operate in silos [6], [22]. Future research should focus on developing robust mechanisms for interoperability between different blockchain networks (both public and private) and legacy systems [25]. This would enable seamless data exchange and collaboration across diverse SC ecosystems that may use different blockchain solutions. Solutions like Polkadot [41], [44] or Cosmos [39], which focus on creating networks of blockchains, offer potential pathways [6], [25].
- **Data Standards and Semantics:** Establishing common data standards, ontologies, and semantic frameworks for representing SC events and product information is critical [3], [10], [45], [61]. This will ensure that data recorded on different systems can be understood and processed consistently, facilitating true end-to-end traceability and analytics.

Scalability, Performance, and Energy Efficiency of Blockchain

- **Advanced Consensus Mechanisms:** Research into more scalable and energy-efficient consensus algorithms beyond traditional PoW is ongoing. Alternative mechanisms like PoS variants, PoA, and Directed Acyclic Graphs (DAGs) (e.g., IOTA, Hashgraph) need further investigation for their suitability in high-throughput manufacturing environments [22], [40], [62].
- **Layer-2 Scaling Solutions:** Exploring and refining Layer-2 scaling solutions such as state channels, sidechains, and rollups can help improve transaction speeds and reduce costs on main blockchain networks, making them more viable for large-scale industrial applications [6], [37], [41].
- **Lightweight Clients and Edge Integration:** Developing lightweight blockchain clients and efficient integration methods for resource-constrained IoT devices and edge computing nodes will be vital for real-time data capture and processing at the source [19], [37], [39].

Advanced AI and ML Integration

- **Federated Learning for Privacy-Preserving AI:** To address data privacy concerns when training AI models on sensitive SC data from multiple organizations, federated learning is a promising approach [18]. This allows models to be trained collaboratively without sharing the raw data itself, with only model updates being exchanged.

- **Explainable AI (XAI) for Trust and Auditing:** As AI plays a more significant role in decision-making within traceability systems, developing XAI techniques is crucial. This will make AI-driven insights and actions more transparent, understandable, and auditable, building trust among stakeholders and facilitating regulatory compliance [17].
- **Reinforcement Learning for Dynamic Optimization:** Applying reinforcement learning to optimize complex SC processes, such as dynamic routing, inventory management, and production scheduling, in conjunction with blockchain-verified data, could lead to highly adaptive and efficient systems [45].
- **AI for Smart Contract Security:** Research into using AI and formal verification methods to automatically detect vulnerabilities and ensure the correctness of smart contract code can enhance the security and reliability of blockchain applications [17], [18].

Integration with Digital Twins

Creating comprehensive Digital Twins of products, processes, and entire SCs, powered by real-time data from IoT and blockchain, offers immense potential. Future research should explore how blockchain can provide a trusted data backbone for these Digital Twins, enabling more accurate simulations, predictive analytics, and what-if scenario modeling for enhanced decision-making and operational resilience [6], [17], [20], [45].

Quantum Computing Impacts and Post-Quantum Cryptography

While still in its nascent stages, the advent of quantum computing poses a potential long-term threat to current cryptographic algorithms used in blockchain technology. Research into post-quantum cryptography (PQC) and its integration into blockchain platforms will be necessary to ensure the future security and longevity of these systems[23], [37].

Circular Economy and Sustainability Applications

BET can play a substantial role in advancing the circular economy by tracking materials through their lifecycle, verifying recycling processes, and ensuring responsible sourcing [6], [25], [27], [41], [63]. Future research can explore novel applications for:

- **Product Lifecycle Management:** Tracking products from cradle-to-grave or ideally cradle-to-cradle to facilitate reuse, remanufacturing, and recycling [18], [20].
- **Carbon Footprint Tracking:** Accurately measuring and verifying the carbon footprint of products and SC operations [8], [14].
- **Ethical Sourcing Verification:** Providing immutable proof of ethically sourced materials and fair labor practices [6], [25].

Governance Models for Decentralized Autonomous Organizations (DAOs)

Exploring how DAOs, governed by smart contracts and community consensus, could manage and operate decentralized traceability networks is an intriguing research direction. This could lead to more democratic and robust SC ecosystems, though challenges related to legal recognition and practical implementation need to be addressed [18].

By pursuing these research directions, the academic and industrial communities can collectively push the boundaries of what is possible with BET in SM, leading to more intelligent, secure, efficient, and sustainable global SCs.

CONCLUSION

Summary of Key Contributions and Findings

This research has comprehensively studied the transformative potential of integrating blockchain technology with AI and IoT to enhance traceability, data integrity, and transparency within SM environments. We have established that the inherent characteristics of blockchain—decentralization, immutability, and cryptographic security—provide a robust foundation for addressing the persistent challenges in modern SCs, such as counterfeiting, quality control deficiencies, and lack of end-to-end visibility [2]. The proposed system architecture, layered to incorporate physical data acquisition via IoT, secure data transmission, a core blockchain layer with smart contracts, and an application layer for analytics and user interaction, offers a viable framework for practical implementation.

The examination of diverse use cases across key sectors: automotive, pharmaceuticals, and electronics—has underscored the tangible benefits. These include significantly improved product authentication, more efficient recall management, verifiable cold chain integrity, enhanced regulatory compliance, and greater consumer trust. The synergy with AI allows for advanced analytics on blockchain-verified data, enabling predictive insights and automated decision-making, while IoT provides the real-time data streams crucial for a dynamic and responsive traceability system [19], [33].

Policy and Practical Implications

The findings of this research provide noteworthy policy and practical recommendations. For policymakers, fostering the adoption of these advanced traceability systems requires creating supportive regulatory frameworks that recognize blockchain-based records and smart contracts. Investment in digital infrastructure and initiatives to enhance digital literacy and skills are crucial to ensure equitable access and benefit [20]. Furthermore, promoting industry-wide standards for data exchange and interoperability will be vital for creating cohesive and efficient SC ecosystems.

For industry practitioners, the adoption of BET necessitates a strategic approach. This includes careful consideration of the specific challenges within their sector, a clear understanding of the costs and benefits, and a phased implementation plan. Collaboration among SC partners is key, as the value of a shared ledger is maximized when all relevant stakeholders participate. Businesses should also prioritize robust governance models for their blockchain consortia and invest in cybersecurity measures to protect the entire system. The potential for enhancing sustainable industrial development, by verifying ethical sourcing, tracking carbon footprints, and promoting circular economy principles, offers a compelling value proposition beyond mere operational efficiency [17].

Concluding Remarks and Vision for the Future

Blockchain technology, when synergistically combined with AI and IoT, stands as a cornerstone for the next generation of SM. It offers a pathway to overcome the drawbacks of traditional traceability systems, paving the way for SCs that are not only more efficient and secure but also more transparent, accountable, and sustainable. While challenges related to scalability, interoperability, and regulation persist, ongoing research and technological advancements, as discussed in the future research directions, are continuously addressing these hurdles.

The vision for the future is one where intelligent manufacturing ecosystems are built on a foundation of trust, enabled by verifiable data and automated processes. BET will be instrumental in realizing this vision, empowering businesses to meet the evolving demands of consumers and regulators and contributing to a more robust and responsible global economy. The journey towards fully integrated and intelligent traceability is an ongoing one, but the transformative potential is undeniable, promising a new era of integrity and insight in the world of manufacturing.

STATEMENTS AND DECLARATIONS

Competing Interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Funding

The authors did not receive support from any organization for the submitted work.

Author Contributions

Ahmad Muhammad Tahir conceptualized and wrote the manuscript. Garima Joon and Umema Ahmed provided critical guidance and revised the manuscript. All authors have read and approved the final manuscript.

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